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SIMULATION USING GIPPS' CAR-FOLLOWING MODEL – AN IN-DEPTH ANALYSIS

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This study reports on an in-depth analysis of the properties of Gipps' car-following model. Certain properties of the model are investigated and the need of specific additions to the model is identified. Gipps' car-following model is rather important as it comprises the traffic model of several traffic simulation packages; and the analysis performed in this study determines the actual dynamics that govern model formulae. First, the relationships for the maximum acceleration and deceleration values the model produces are identified. Results indicate that model relationships are such that a vehicle could end up braking harder than its desired deceleration, hence a constraint has to be set. Furthermore, relationships between vehicle acceleration and speed are established. Second, further additions are proposed to allow the model simulate traffic at signal-controlled junctions. These additions include providing a definition for a queueing vehicle and speed manipulation to achieve the calculated saturation flow of simulated junctions.

KEYWORDS: Acceleration, deceleration, model properties, saturation flow, traffic model

1. INTRODUCTION

Traffic flow theory originated in the 1930's with the application of probability theory for the description of road traffic. Greenshields (1935) investigated the relationships between traffic volume and speed as well as traffic performance at intersections. Since then traffic flow theory has evolved and a wide range of models to describe traffic movement has been developed including microscopic, mesoscopic and macroscopic ones. In a microscopic analysis, the movement of single elements and the interaction between them is represented explicitly (by the term single elements, vehicles or pedestrians are implied). In a macroscopic analysis, an aggregation of the behaviour and movement of single elements into that of larger quantities of traffic is used. Intermediate between these two levels of analysis is the mesoscopic one: in this kind of analysis, the movement of aggregated single elements is represented, but the model comprises complementary combinations of macroscopic models, each compensating for the shortcoming of others.

The first milestone in the development of traffic models was Lighthill and Whitham's model (1955) which was based on the assumption that vehicle movement in traffic flow presents similarities with particle movement in fluid, and is a macroscopic model. Car-following models are microscopic models as they describe the behaviour of individual drivers when interacting with vehicles in their proximity, and were introduced in the 1950's. The principle theory is that each driver reacts to the stimulus he/she receives from other traffic by accelerating or decelerating (Chowdhury et al., 2000). The speed of the preceding vehicle, the relative speed difference between the simulated vehicle and its preceding, the space headway etc. are some of the elements that may comprise the stimulus as defined in the different models.

Car-following theory originates with Herrey and Herrey in 1945 who suggested that drivers keep a "minimum safe distance" from the preceding vehicles, which forms the

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basic concept of all car-following models with some modifications (stimulus response). Car-following theory was first suggested by Pipes (1953), and then discussed by Kometani and Sasaki (1958), Chandler et al. (1958), Gazis et al. (1959), Gazis et al. (1961) and Newell (1961) amongst others. Gipps's car-following model was developed in 1981 (Gipps, 1981) and was based on the assumption that a driver sets limits to his desired braking and acceleration. Gipps (1986a) developed his theory further to include lane-changing behaviour in his model.

Gipps' car-following model has formed the basis for simulation software MULTISIM (Gipps, 1986b) and also for a number of traffic simulation software packages including SIGSIM (Silcock, 1993), SISTM (1993), AIMSUN (Barcelo and Ferrer, 1994) and SITRAS (Hidas, 1998; Hidas and Behbahanizadeh, 1998). Yet, even as traffic-flow theory is more easily characterised through advanced computation technology, the fundamentals are just as important today as in the early days (Lieu, 1999). They form the foundation for all the theories, techniques, and procedures that are being applied in the design, operation, and development of advanced transportation systems. For this reason the understanding of the theory behind the application is of great importance. The prerequisite for an efficient application of the model for the simulation of simple or complex networks and scenarios and the interpretation of the simulation results is to understand the model properties and dynamics. Car-following theory and dynamics have been investigated and updated models that produce better results including the optimal velocity model (OVM) (Bando et al., 1995), the generalised force model (GFM) (Helbing and Tilch, 1998) and full velocity difference model (FVDM) (Jiang et al., 2001) have been suggested. However, little work has been performed into interpreting Gipps' model. Ranjitkar et al. (2005) apply and evaluate Gipps' car-following model and state that specific properties of the model have been set arbitrarily by Gipps, whereas this is not the case. Research on the dynamics of Gipps' model has been conducted by Wilson (2001) who applied Gipps' car-following model for simulation of highway traffic and performed linear stability analysis to identify stable and unstable regimes. Still, the simple properties of the model (speed, acceleration, deceleration, reaction time) and their dynamics have not been investigated.

The aim of the paper is to identify the dynamics of the model as these are represented by two of its basic parameters – namely the acceleration and deceleration. Furthermore, possible additions to the model are discussed so that it can simulate urban networks comprising signal-controlled junctions in an efficient way. In the next section, Gipps' car following model is presented. In Section 3, the model parameters are presented and investigated. These parameters include the vehicle speed, acceleration and deceleration that the simulation produces. In Section 4, the appropriation of the model is discussed to allow for efficient simulation of signal controlled junctions. Finally, in Section 5, the main findings of the study are discussed.

2. GIPPS' CAR-FOLLOWING MODEL

2.1 Description of the model

Gipps' car-following model is a microscopic model; it was primarily used for simulating motorway roads. It is quite detailed, and there is a trade-off with computational time, which is long by comparison with other simpler models. Gipps' car-following model is vehicle orientated, thus space is not represented directly in the simulation, and in each time-step certain characteristics of each vehicle are calculated.

Hence, the model is a discrete time, continuous space one. The primary quantity that is calculated is the vehicle's speed and through this its new position. The formula that is used to calculate the "updated" speed (speed at time $t+\tau$) is:

$$u_n(t+\tau) = \min\{G_\mathrm{a}(t), G_\mathrm{d}(t)\}\ , \tag{1a}$$

where

$$G_\mathrm{a}(t) = u_n(t) + 2.5a_n\tau\left(1 - u_n(t)/V_n\right)\sqrt{0.025 + u_n(t)/V_n}\ , \tag{1b}$$

$$G_\mathrm{d}(t) = b_n\tau + \sqrt{b_n{}^2\tau^2 - b_n\left(2\left(x_{n-1}(t) - s_{n-1} - x_n(t)\right) - u_n(t)\tau - u_{n-1}(t)^2/\hat{b}\right)}\ , \tag{1c}$$

$u_n(t)$ is the speed of vehicle *n* at time *t*, a_n is the maximum acceleration which the driver of vehicle *n* wishes to undertake, τ is the apparent reaction time (the same constant for all vehicles), V_n is the speed at which the driver of vehicle *n* wishes to travel, b_n is the most severe braking that the driver of vehicle *n* wishes to undertake ($b_n < 0$), $x_n(t)$ is the location of the front of vehicle *n* at time *t*, s_n is the effective size of vehicle *n*, that is, the physical length plus a margin into which the following vehicle is not willing to intrude, even when at rest, and $\hat{b}$ is the value of b_{n-1} estimated by the driver of vehicle *n* who cannot know this value from direct observation.

The formula for the estimation of vehicle speed comprises two parts: the accelerating part (1b) and the decelerating part (1c). In a simulation, both terms are calculated and the minimum speed is used as the updated speed. The speed from (1b) is estimated taking into account the characteristics of the simulated vehicle *n* – namely the ratio of its current speed and desired speed $u_n(t)/V_n$ and its maximum acceleration a_n. This is the speed that a vehicle would obtain if its movement is not impeded by the movement of the preceding vehicle. The speed from (1c) is estimated also taking into account the characteristics of the preceding vehicle – namely its speed $u_{n-1}(t)$, and position $x_{n-1}(t)$ and effective size s_{n-1} (to estimate the space headway) as well as some of the properties of the simulated vehicle including deceleration properties. In this case, the movement of the simulated vehicle is impeded by that of the preceding vehicle and hence its speed is also dependant on the properties of the preceding vehicle. If the movement of the simulated vehicle is not impeded by the preceding vehicle, the speed estimated by (1b) is lower than that of (1c), and comprises the updated speed. In the opposite case, the speed (1c) is lower than that of (1b) and comprises the updated speed. In general, if the limiting condition for vehicles in a link is (1b) this indicates that traffic is flowing freely, whereas if the limiting condition is (1c) then the link is congested.

In addition, the position of vehicle *n* at time $t+\tau$ will then be:

$$x_n(t+\tau) = x_n(t) + 0.5\left(u_n(t) + u_n(t+\tau)\right)\tau\ . \tag{2}$$

2.2 Representation of moving vehicles

These two quantities, the vehicle speed and position at the end of every time-step, are used to represent vehicle movement in a network. The vehicle speed and trajectories can be deduced from these data as the simulation output, and an example is illustrated in Figures 1 and 2.

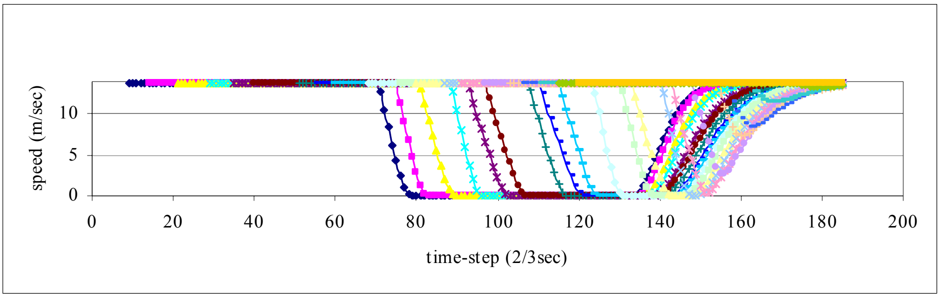

FIGURE 1: Vehicle speed in relation with time

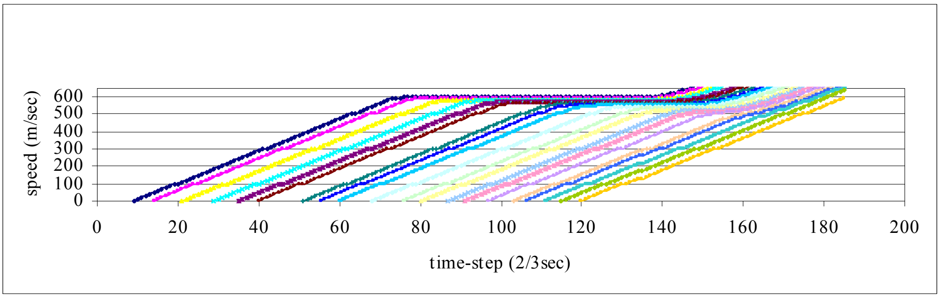

FIGURE 2: Vehicle trajectories

The simulated network consists of a 600 m link at the downstream end of which is a signal-controlled junction, with a 90-second cycle and 40-second green indication time. Vehicles enter the simulation at free-flow speed (13.89 m/sec) and approach the stop-line. The first vehicle reaches the stop-line when the signal indication is red and vehicles start queuing behind it. Once the signal turns to green, vehicles start accelerating and the queue starts dissipating, while the back of the queue grows upstream. The last simulated vehicle arrives when the queue has already dissipated, and thus travels unimpeded at free-flow speed throughout the link. Figure 1 shows that vehicle speed traces are overlapping, which does not cause any problems. Vehicle trajectories, however, should not overlap, as this could mean vehicle overtaking (which cannot happen in the simulated scenario) or vehicles crashing.

3. MODEL PARAMETERS

3.1 Description of model parameters

The parameters used in Gipps' car-following model are quite detailed as this is a microscopic model. These parameters are the time-step (which corresponds to the drivers' reaction time), vehicles' maximum acceleration and deceleration, their effective length, their desired speed and an estimate of the preceding vehicle's braking.

Specific values were allocated to these parameters by Gipps for his validation of the model. The time-step has a set value of 2/3 seconds, and this value is a limiting aspect of the model. Time-step does not have an integer value, and this can make several simple aspects of programming and comparing Gipps' results to those of other models more complicated. The maximum acceleration a_n is sampled from a normal distribution

N(1.7,0.3^2) m/sec^2. The maximum desired deceleration b_n is set to $-2.0a_n$. The effective length s_n of a vehicle and its desired speed V_n are sampled from normal populations N(6.5,0.3^2) m and N(20.0,3.2^2) m/sec, respectively. The estimate of the preceding vehicle's braking $\hat{b}$ is equal to the minimum of -3.0 and $(b_n - 3.0)/2$ m/sec^2.

One of the advantages of the model is that each vehicle is assigned different characteristics (resulting from the different values of the parameters), which is representative of reality. Different vehicles have different mechanical characteristics, which result in different maximum accelerations and decelerations. In addition, different vehicles have different drivers, who differ in their driving behaviour. This is also embodied in the different desired speeds, acceleration and decelerations, and effective lengths. The mean values of the normal distributions that are used to calculate the parameters can be changed for different vehicle categories and networks. According to the needs of the use of the model, the user must decide on the model parameters. This might make the model more complicated but also more detailed and representative of reality. An example is the mean desired speed. Gipps' validation of the model used a simulation of vehicles moving on a highway. In cases where the simulated networks are urban the desired speed has to be lower than that used by Gipps. This could also result in different values of maximum acceleration and deceleration. Such parameter modifications can be made, but their validation is required.

3.2 Analysis of the model parameters

3.2.1 Accelerating term

The speed of a vehicle is derived from Gipps' equation at each time-step. This speed should be such that it does not produce acceleration or deceleration values greater than the maximum desired ones assigned for each vehicle. Using Gipps' equation for speed after accelerating (1b), the acceleration undertaken by a vehicle can be calculated, and is:

$$a = 2.5a_n\left(1 - u_n(t)/V_n\right)\sqrt{0.025 + u_n(t)/V_n}\ . \tag{3}$$

For analysis purposes the value 0.025 will be denoted with dummy variable c. To compute the boundary values of the acceleration its first derivative with respect to $u_n(t)$ has to be calculated and set to zero.

$$\frac{\mathrm{d}\,\alpha}{\mathrm{d}(u_n(t))} = \left(c + u_n^*/V_n\right) - \frac{1}{2}\left(1 - u_n^*/V_n\right),$$

$$\frac{\mathrm{d}\,\alpha}{\mathrm{d}(u_n(t))} = 0\ ,$$

$$u_n^* = \frac{1-c}{3}V_n\ .$$

For this value of the speed, the acceleration takes a maximum or minimum value. The second derivative of the acceleration will also be calculated to check whether the acceleration takes a maximum or minimum value. Thus,

$$\frac{\mathrm{d}^2\,\alpha}{\mathrm{d}(u_n(t))^2} = -\frac{1}{V_n^2}2.5a_n\left(\left(c + u_n^{**}(t)/V_n\right)^{-1/2} + \frac{1}{4}\left(1 - u_n^{**}(t)/V_n\right)\left(c + u_n^{**}(t)/V_n\right)^{-3/2}\right),$$

which is clearly negative. Thus, for $u_n^* = (1-c)V_n / 3$ the acceleration takes a maximum value.

Replacing $u_n(t)$ with the above value in the acceleration equation (3) the maximum acceleration that a vehicle can have is obtained, and is:

$$a = 2.5a_n \left(1 - u_n^* / V_n\right)\sqrt{c + u_n^* / V_n} \ . \tag{4}$$

In Gipps' case, where $c = 0.025$, the maximum acceleration that a vehicle can have is $0.998599a_n$, which is almost equal to a_n. Thus, the acceleration of vehicle n will never exceed the value of the parameter a_n. Furthermore, by solving equation (3) as $a = a_n$, one can find the value of c that would provide the maximum acceleration of vehicle n to be equal to the parameter a_n. This is $c = 0.025985568006$.

It should be noted that the reason for the non-zero value of parameter c being added to $u_n(t)/V_n$ in the acceleration speed formula (1b) is to allow vehicles to start moving from stationary. Otherwise, vehicles that at some point in time have speed equal to zero, will have a new speed, calculated from the accelerating speed, which can only be zero, and these vehicles will remain stationary throughout the simulation. Furthermore, if there were no value added to $u_n(t)/V_n$, thus for $c = 0$ the maximum acceleration that a vehicle could have, would be $0.96225a_n$, which is even lower than the acceleration that a vehicle can have with this value (0,025) being added. Hence, the value 0.025 is not chosen arbitrarily which contradicts what Ranjitkar et al. (2005) state.

As described before a vehicle on an otherwise empty road starts accelerating from zero speed towards its desired one. The relationship between the actual and maximum values of acceleration α / α_n in relation to those of speed u_n / V_n can be deduced and is:

$$f(x) = \frac{\sqrt{x^3 - 2.025x^2 + 1.05x - 0.025}}{2.5}, \tag{5}$$

where $x \equiv u_n / V_n, R \in [0,1]$ and $f(x) \equiv \alpha / \alpha_n, R \in [0,1]$.

Equation (5) is graphically described in Figure 3 and represents a vehicle moving unimpeded from zero to its desired speed.

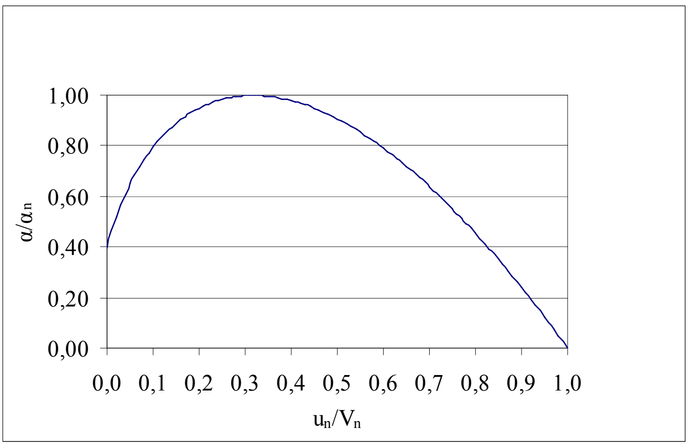

FIGURE 3: Acceleration in relation to speed

A stationary vehicle that starts to move, has an acceleration of $0.3953a_n$ and continues moving towards its desired speed with increasing acceleration, up to the point where speed is $u_n^* = 0.95V_n / 3$. At this point the acceleration reaches its maximum value, which is $a = 0.998599a_n$. From this point, the vehicle continues accelerating towards its desired speed, but with falling acceleration.

Using Gipps' accelerating speed formula and typical values for parameters a_n and V_n, which are 1.7 m/sec^2 and 14 m/sec respectively, the relationship between the new speed $u_n(t+\tau)$ and the old speed $u_n(t)$ can be derived, and is shown graphically in Figure 4. The reason for this presentation is to show how similar these two lines are in general terms, but also to demonstrate their difference.

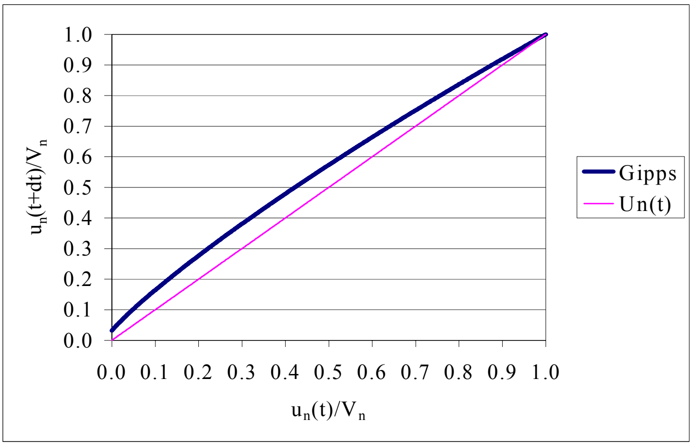

FIGURE 4: Speed at time-step (t+dt) in relation to speed in time-step t

All speeds in this figure are presented as a proportion of the desired speed, V_n. The Gipps labelled line corresponds to the speed that is derived using Gipps' formula. The $u_n(t)$ line is the line that corresponds to $u_n(t+\tau) = u_n(t)$. The speed at the time-step t+τ is slightly greater than the speed at t. Also the line of $u_n(t+\tau)/V_n$ using Gipps' formula is slightly curved, and the difference between $u_n(t+\tau)$ and $u_n(t)$ is greatest at the point where $u_n(t) = 0.95V_n / 3$.

3.2.2 Decelerating term

Whether the deceleration of a vehicle is higher than its maximum desired value should also be examined. The speed when a vehicle is decelerating is shown in equation (1c):

$$u_n(t+\tau) = b_n\tau + \sqrt{b_n{}^2\tau^2 - b_n\left(2\left(x_{n-1}(t) - s_{n-1} - x_n(t)\right) - u_n(t)\tau - u_{n-1}(t)^2 / \hat{b}\right)},$$

and the derived deceleration is:

$$b = \frac{b_n\tau + \sqrt{b_n{}^2\tau^2 - b_n\left(2\left(x_{n-1}(t) - s_{n-1} - x_n(t)\right) - u_n(t)\tau - u_{n-1}(t)^2 / \hat{b}\right)} - u_n(t)}{\tau}. \quad (6)$$

The parameter $\hat{b}$ is the maximum braking that the driver n estimates that vehicle $n-1$ can have. Thus, the speed of vehicle n is calculated on the assumption that the vehicle $n-1$ does not have deceleration greater than that. However, if the deceleration of vehicle $n-1$ is greater, vehicle n might need to brake more sharply than b_n. In addition, a vehicle might need to brake more sharply than b_n if when approaching the stop-line the signal turns to red or in cases or sharp braking of the vehicle in front. A set of values are used to prove the point that equation (6) can produce values higher than the desired deceleration b_n. The example describes the case of a vehicle approaching the stop-line (positioned at 500 metres) at free-flow speed while the signal turns to amber. Its parameters are: b_n = -2.70 m/sec^2, $\hat{b}$ = -2.85 m/sec^2, $x_n(t)$ = 470 m, and $u_n(t)$ = 14 m/sec.

The vehicle has to stop at the stop-line and since there is no vehicle upstream of the stop-line, a "phantom" vehicle is introduced as the preceding vehicle $n-1$. Its settings, which will be discussed later, are: $x_{n-1}(t)$ = 500 m, s_{n-1} = 0 m, and $u_{n-1}(t)$ = 0 m/sec.

Time-step τ takes its default value 2/3 s, and the deceleration of vehicle n is calculated and is b = 5.95 m/sec^2. The calculated value of the vehicle deceleration is greater than the maximum desired one.

This illustrates that the deceleration of a vehicle is not always less or equal to the set deceleration parameter b_n, hence a constraint has to be set, to avoid vehicles decelerating at higher rates than the maximum they can "use". In each time-step after the speed of a vehicle is calculated, its actual deceleration is calculated as

$$\text{Actual deceleration} = \frac{u_n(t+\tau) - u_n(t)}{\tau}, \tag{7}$$

and compared to its maximum desired value b_n. If the calculated deceleration is greater than the maximum desired one, the new deceleration of the vehicle i.e. the one applied at time-step (t+τ) is set equal to its set value b_n and the new speed at time-step (t+τ) is recalculated from equation (7), using b_n as the deceleration value.

This should be applied with care since there might be a trade-off between vehicles obtaining higher deceleration values than their set maximum ones b_n and potential vehicle collisions. Hence, the user should define whether the primary aim is for vehicles not to collide with other vehicles (or pass a red signal) or not to obtain higher deceleration values than the set maximum ones. Helbing and Tilch (1998) developed a generalised force model (GFM) based on car-following theory, which performed well in situations of vehicles approaching standing cars in which other car-following models would produce collisions, by guaranteeing early and sufficient braking especially in cases of large differences in the speeds of the simulated vehicle and its preceding one. Applying their theory in Gipps' model one could eliminate the possibility of potential collisions.

3.2.3 Cruising at constant speed

According to Gipps' model, vehicles accelerate and decelerate depending on the circumstances. There are also special cases when they travel at constant speed. The circumstances under which this happens are investigated, solving the following equation.

$$u_n(t+\tau) = u_n(t)\,. \tag{8}$$

If the vehicle movement is not influenced by that of the preceding vehicle the investigated vehicle is in a position to accelerate, and the first part of Gipps' formula (1b) is used for calculating the new speed, thus

$$u_n(t) = u_n(t) + 2.5a_n\tau\left(1 - u_n(t)/V_n\right)\sqrt{0.025 + u_n(t)/V_n}\,,$$

$$\Rightarrow \qquad 2.5a_n\tau\left(1 - u_n(t)/V_n\right)\sqrt{0.025 + u_n(t)/V_n} = 0\,,$$

$$\Rightarrow \qquad u_n(t) = V_n\,.$$

This was expected since if a vehicle can accelerate it will do so until it reaches its desired speed and then continue travelling at it, if not impeded by the movement of the preceding vehicle. However, if the vehicle movement is influenced by that of the preceding vehicle, the decelerating part of Gipps formula is used; formula (1c), and is:

$$u_n(t) = b_n\tau + \sqrt{b_n{}^2\tau^2 - b_n\left(2\left(x_{n-1}(t) - s_{n-1} - x_n(t)\right) - u_n(t)\tau - u_{n-1}(t)^2/\hat{b}\right)}\,,$$

$$\Rightarrow \qquad u_n(t) = \frac{3b_n\tau \pm \sqrt{9b_n{}^2\tau^2 - 4b_n\left(2\left(x_{n-1}(t) - s_{n-1} - x_n(t)\right) - u_{n-1}(t)^2/\hat{b}\right)}}{2}\,.$$

The speed can only take positive values, hence the solution will be:

$$u_n(t) = \frac{3b_n\tau + \sqrt{9b_n{}^2\tau^2 - 4b_n\left(2\left(x_{n-1}(t) - s_{n-1} - x_n(t)\right) - u_{n-1}(t)^2/\hat{b}\right)}}{2}\,.$$

This shows that in both conditions, not-impeded and impeded by the preceding vehicle, a simulated vehicle can cruise at constant speed.

4. USING THE MODEL FOR TRAFFIC SIMULATION OF SIGNAL-CONTROLLED JUNCTIONS

This section describes the way in which Gipps' car-following model is set for traffic simulation in urban networks with signal-controlled junctions. In particular, Gipps' car following model was developed for simulation of highway traffic, hence certain constraints and elements have to be added to the model to simulate vehicles more efficiently.

4.1 "Phantom" vehicle applications

One of the important issues involving the simulation using Gipps' car-following model is how to make vehicles stop at traffic signals. A vehicle, according to Gipps' formula, adjusts its speed depending on the position and speed of the vehicle in front. There is no parameter that can be manipulated in order to make a vehicle stop at the stop-line of a junction when the signal is red. Thus, the concept of a "phantom" vehicle can be introduced. This concept has been previously deployed in other micro-simulation packages including NETSIM (Federal Highway Administration, 1980). The way the "phantom" vehicle is operated is that when the signal indication turns to red, this notional vehicle is placed in such a position and with such characteristics that the first vehicle upstream that approaches the junction during the red period follows this vehicle, and comes to a stop at the stop-line. Thus, the "phantom" vehicle should be placed just downstream of the stop-line with zero speed. Because this vehicle will be used in Gipps' formula certain parameters for it have to be set. From Gipps' formula (1) in order to calculate a vehicle's speed at time $(t+\tau)$ the parameters of the preceding vehicle $(n-1)$ are its speed $u_{n-1}(t)$ and position $x_{n-1}(t)$ at time t and the space s_{n-1} it occupies including a distance it keeps from the vehicle that is in front of it. The "phantom" vehicle has to be stationary and thus, its speed has to be zero. The space it occupies is set to zero, and so its position is at the stop-line of the junction, in order for the following vehicle to stop just upstream of the stop-line. Giving the vehicle a spacing of 6.5 metres which is the average spacing that is used for the simulation with Gipps' model, and a position of 6.5 metres downstream of the stop-line is also an option, which produces the same result. The first one is preferred as a concept, since it seems more suitable for a "phantom" vehicle to occupy zero space. Furthermore, such an assumption could create possible conflicts with vehicles located just downstream of the stop-line.

4.2 Selection of first vehicle to stop at the stop-line

The second issue is a consequence of the first one. Once the signal turns to red and the "phantom" vehicle is set, the first vehicle *n* upstream of the junction has one of its settings changed. Its preceding vehicle is no longer the $(n-1)$ vehicle, but the "phantom" vehicle instead. This is now the vehicle that vehicle *n* follows. The issue that arises from this is that it is not certain that vehicle *n* will be able to come to a stop upstream of the stop-line. It could be that its position and speed are such that it will "crash" with the phantom vehicle. Thus, a condition has to be set to test whether a vehicle will be able to stop at the stop-line. If this condition is satisfied then its preceding vehicle will be the "phantom" vehicle. If not then, the same procedure will be placed upon the next vehicle upstream, and this scanning will continue until a vehicle that has such characteristics is found. So, this vehicle will come to a stop at the stop-line, if it reaches the stop-line during the red period, and the vehicles that are upstream of it, will follow it and start forming a queue. The condition that has to be satisfied so that a vehicle will be able to stop at the stop-line follows:

$$x_J - x_n(t-\tau) \geq \frac{u_n^2(t-\tau)}{2b_n}, \tag{9}$$

where x_J is the position of the stop-line at the junction.

Thus, the left hand-side of equation (9) is the distance that the vehicle has to travel in order to arrive at the stop-line. The right hand-side of equation (9) is the distance that the vehicle will travel at this time-step with its maximum desired deceleration. This distance should be smaller than the distance between its position and the stop-line, which is what this inequality states. There can be cases though, when the vehicle is already too close to the junction when the signal turns to red. In such cases, the above condition might be satisfied, but also vehicle *n* might be able to pass from the stop-line before the signal turns to red. Thus, a second condition has to be added, to allow vehicles that can to pass the stop-line before the signal turns to red, and thus to select the first vehicle that cannot leave the junction during the green period and place downstream the "phantom" vehicle. If the condition below is satisfied the vehicle will follow the "phantom" vehicle and thus decelerate and come to a stop at the stop-line; otherwise it will continue following the vehicle in front.

This condition is:

$$u_n(t-\tau)t_l < x_J - x_n(t-\tau), \quad (10)$$

where t_l is equal to the time from the instance that the driver "sees" the signal not being green until the start of the red stage. Thus, if the signal is amber t_l will fit the above definition and if it is already red it will be equal to zero.

4.3 Modification for saturation flow

Another shortcoming using Gipps' model for simulation, is that there is no parameter that specifies directly the amount of traffic that can pass through a junction. Thus, the saturation flow of the simulation is equal to the saturation flow that the model produces, and there is no direct parameter that can be set so that the saturation flow of the simulation is equal to that which the simulated junction would provide. A way of overcoming this problem is by manipulating the desired speed of vehicles in the vicinity of the junction. This manipulation will be applied for a zone upstream and downstream of the junction. This zone was set to be 50 metres before and 5 metres after the junction (Law and Crosta, 1999), but other values can also produce good results. A smooth reduction of the speed which is also related to the distance between the position of the vehicle and the stop-line will produce more realistic results. Hence, a reduction factor is applied to the desired speed of vehicles positioned within this zone, and is dependant on the exact position they have within the zone. It provides a speed reduction at the stop-line and a smooth increase to the normal desired speed on either side of the stop-line. This factor is calculated using the Gaussian function, and the formula follows:

$$g = 1 - \alpha_g \exp\left(-\frac{x_1^2}{2l_1^2} - \frac{x_2^2}{2l_2^2}\right), \quad (11)$$

where g is the factor applied to each desired speed, α_g is the greatest percent speed reduction expressed as a fraction, x_1 is the distance between the vehicle position and the stop-line or zero if vehicle is downstream of the stop-line, thus $x_1 = \max\{x_J - x, 0\}$ with x_J being the position of the junction and x the position of the vehicle, x_2 is the distance between the stop-line and the vehicle position or zero if vehicle is upstream of the stop-line, thus $x_2 = \max\{x - x_J, 0\}$, $3l_1$ is the zone of influence upstream of the stop-line (50 metres), and $3l_2$ is the zone of influence downstream of the stop-line (5 metres).

Specifying l_1 and l_2 in this way is a result of the Gaussian function becoming negligible at 3 standard deviations from the mean.

The graphical representation of the vehicle reduction factor g as obtained from equation (11) is illustrated in Figure 5 (for the example α_g is set to 0.6).

In order to achieve the desired saturation flow during a simulation, saturation flow is measured at the simulated junction using one of the well-established calculation methods (Road Research Laboratory, 1963; Transportation Research Board, 2000) for certain values of α_g. The simulation is then run with the value of α with which the desired saturation flow is achieved. An example relationship between the derived saturation flow and the value of α_g for a single lane is illustrated in Figure 6 (based on Silcock, 1993).

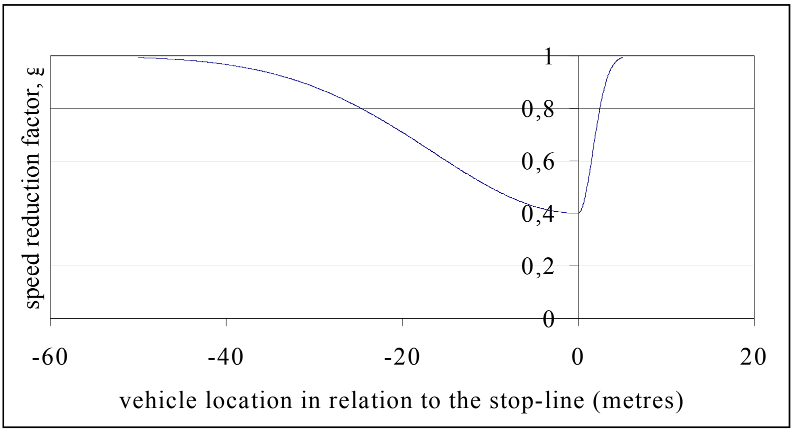

FIGURE 5: The Gaussian distribution used to decrease desired speeds at the stop-line

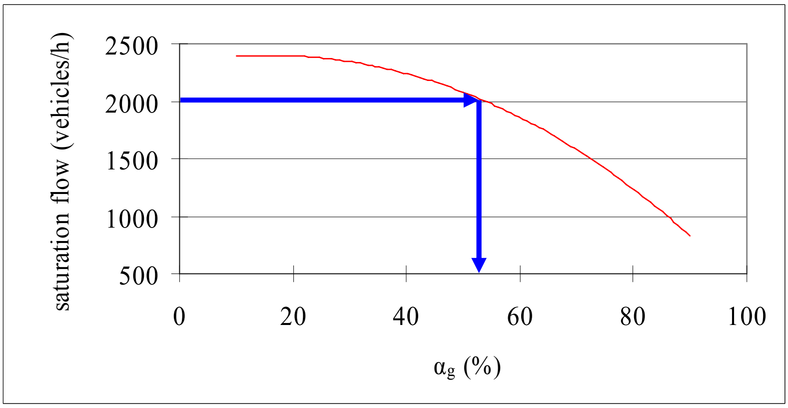

FIGURE 6: Saturation flow (vehicles/hour) against speed reduction (%)

The relationship between saturation flow and the parameter α_g is dependant on the position of speed reduction zone (l_1 and l_2) in relation to the junction stop-line, as well as the type of simulated lane (single, nearside or offside) and the parameters used in the Gipps model, ie vehicle effective length s_n, desired speed V, and maximum acceleration a_n. The pattern illustrated remains the same, however absolute values are somewhat different with the modification of the above mentioned parameters. Using the above illustration as an example, if the saturation flow of the simulated lane is 2.000 the value of α_g that should be used to derive it is 50.05.

4.4 Definition of a queuing vehicle

When using Gipps' formula for simulation, vehicles often do not have zero speed when they slow down. This is a characteristic of the model, but in practice this is not how traffic works. However, it should be noted that using typical values, vehicles do come to a complete stop or reach their maximum speed within finite time. This inherent element of the model has to be taken into account when applying rules to define stationary vehicles.

In the saturation flow estimation methods, the user has to decide which vehicles are saturated, by specifying which vehicles are queuing. The safest hypothesis that can be made in order to determine whether a vehicle is queuing is to check whether its speed is zero. However, in simulations using Gipps' model vehicles seldom have zero speed as noted earlier, and so another hypothesis has to be made based on which it will be decided whether a vehicle is queuing or not. The measure of whether a vehicle is queuing was decided to be the distance between this vehicle and the vehicle in front. If this is smaller than a critical value that was defined, then the vehicle is deemed to be in a queue. Thus, a vehicle is supposed to be in the queue if (Crosta, 1999):

$$x_{n-1}(t) - (x_n(t) - s_{n-1}) \leq 2x_q \, ,$$

this zone x_q was decided to be 1.5 metres.

5. DISCUSSION

In this study an in-depth analysis of the parameters of Gipps' model was performed, with the objective of providing insight on the dynamics of the model. This was achieved mainly by investigating the inherit properties of the model. Furthermore, the analysis also consisted of the design and application of rules for the efficient simulation of signal-controlled junctions. Such analysis improves the understanding of the model and of the possible results it may produce when used for simulation through traffic simulation packages.

Gipps' model is a microscopic traffic model which is based on the assumption that drivers adjust their speed, hence accelerate or decelerate depending on the position of the preceding vehicle, whilst having set limits to their maximum desired acceleration and deceleration. These two values comprise two of the fixed input parameters of Gipps' model, and were compared to the acceleration and deceleration values that the model produces. The acceleration of a simulated (using Gipps' model) vehicle does not exceed the desired acceleration parameter. However, the deceleration produced by the simulation can be higher than the set parameter, indicating that a constraint needs to be set. The relationship between speed and acceleration was also established. Vehicles starting at zero speed commence accelerating with increasing acceleration rate up to a point at which the acceleration takes its maximum value. The acceleration then decreases (with a lower rate) up to the point where the vehicle reaches its desired speed and the acceleration is equal to zero.

Gipps' model was also investigated for use of simulating urban traffic at signal-controlled junctions. As the model was initially designed for the simulation of highway traffic several new rules had to be added. The most appropriate way – suited to the nature of the model – to make vehicles stop at the junction stop-line was investigated and the concept of the "phantom" vehicle was discussed. This vehicle has zero speed and occupies zero space, is placed at the junction stop-line when the signal is red and becomes the preceding vehicle of the first vehicle approaching the junction that has to stop for the red signal indication. A rule applying a speed reduction within a zone in the vicinity of the junction stop-line was also introduced to accomplish specific values of junction saturation flow for the simulation. Finally, a rule had to be introduced for determining when vehicles are queueing since vehicles simulated with Gipps' model seldom have zero speed.

Further work on understanding the Gipps' model could involve the sensitivity of the model in relation to the driver reaction time – i.e. the time-step. In addition, investigation of a possible mathematical formula describing the relationship between vehicle properties i.e. desired speed, acceleration and deceleration, the speed reduction factor and the saturation flow would also enhance our knowledge on the model.

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